Final Report: Novel Devices for All-Optical Computing

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Summary

Two novel nonlinear optics devices for serial processing of optical information were investigated. The first-generation devices were all-optical switches in guided wave formats, nonlinear directional couplers and optically tuneable gratings. Waveguides were fabricated in semiconductor-doped glass. For the first time, picosecond switching was demonstrated in a nonlinear directional coupler, a device that is useful for implementating optical logic switching.

Multiple gratings also were fabricated in nonlinear thin film InSb antimonide waveguides and their nonlinear responses were studied. Input grating couplers exhibited a bistable response suitable for optical logic. The reflection and transmission coeficients of a nonlinear distributed feedback grating depend on the incident guided wave beam power. For a weak beam near the Bragg condition, the grating reflectivity was tuned by a strong beam far off the Bragg condition. Finally, the combination of a nonlinear grating input coupler and a nonlinear distributed feedback grating led to bistability at greatly reduced input power levels.
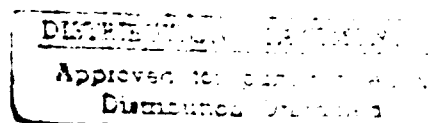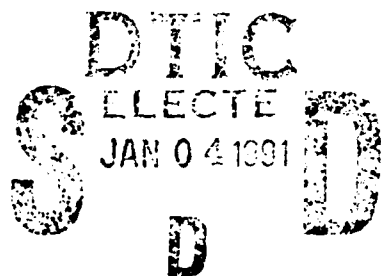
1. Introduction

All-optical switching devices have many applications in optical logic, signal processing and computing. These devices can be implemented either in parallel or serial formats. For-high speed applications, waveguide devices are preferable. In fact, any integrated optics electro-optic switching device can be made into an all-optical device by incorporating a material with an intensity-dependent refractive index. At the inception of this program, no guided wave switching elements had been demonstrated. The two principal all-optical switching devices that were implemented experimentally here are shown in Fig. 1.

(a) Nonlinear Directional Coupler Switch

$$n = n_0 + n_2 I$$
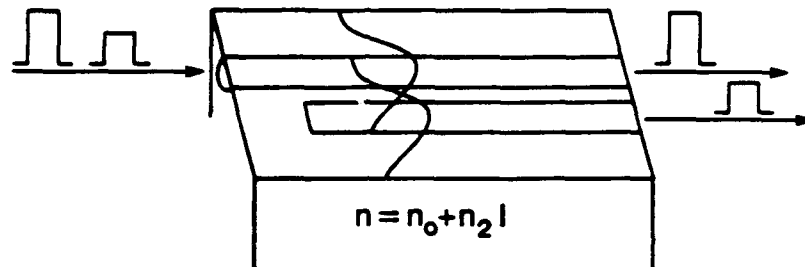
(b) Nonlinear Distributed Feedback Grating Switch
(NLDFG)

Grating

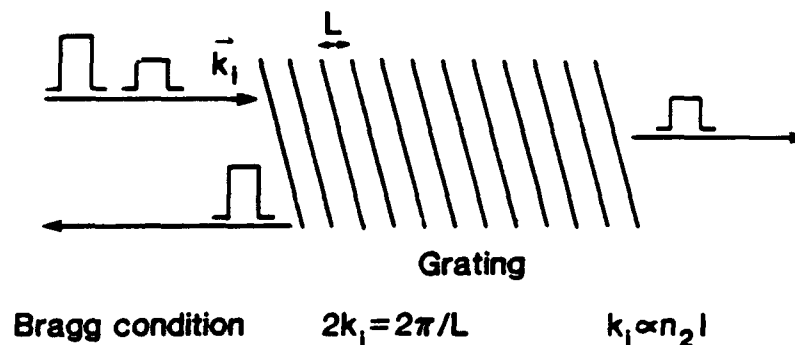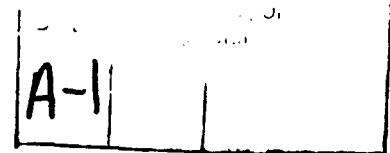Bragg condition $\qquad 2k_i = 2\pi/L \qquad k_i \propto n_2 I$

Fig.1 The two all-optical switching devices investigated: a) half-beat length directional coupler; b) distributed feedback grating reflector.

A nonlinear directional coupler consists of two parallel channel waveguides separated by distances of a few wavelengths. When a single channel is excited, light leaks into the neighboring waveguide with propagation distance if the channels are identical and the device length is properly chosen. Complete transfer can occur. When a high intensity beam is inserted into the input channel, it changes the propagation constant of that channel and mismatches it from its neighboring channel. As a result, the light stays in the input channel. This response corresponds to an all-optical switch.

The operation of a nonlinear grating depends on changes in wavevector matching. For example, in a grating input coupler, optimum coupling efficiency occurs when the projection of the incident light wavevector ± the grating wavevector equals the guided wave wavevector. When the input coupled guided wave changes the guided wave wavevector via its own power, the coupling efficiency is reduced. For a non-local nonlinearity such as a thermal one, bistability can occur under the appropriate detuning conditions. That is the case examined here.

A nonlinear distributed feedback grating also relies on wavevector matching to produce a reflectivity maximum. If the propagation wavevector changes via an increase in power, the Bragg condition is spoiled and the reflectivity changes. This characteristic is useful for all-optical switching.

The following sections describe our implementation of these nonlinear devices during this contract.

2. Nonlinear Directional Coupler

We began by trying to make a nonlinear directional coupler out of color filter glass. There were two factors that made this material an interesting candidate for all-optical switching devices: a) the nonlinear properties of this glass are determined by microcrystallites of CdSSe in the glass and, in this sense, the response is a that of a semiconductor. Also semiconductors had been used successfuly before in etalon switching devices; and b) the color filter glass contains 4% to 12% Na, making it an excellent candidate for fabricating channel waveguides by ion-exchange.

Slab and channel waveguides were made by exchanging the sodium for potassium in the surface region of the color filter glass by immersing the glass into molten potassium nitrate. This required special melts from Schott with sodium content of about 10% to 12%. Propagation losses of less than 0.2 db/cm have been measured in the best samples at the HeNe wavelength of 0.633 μm (far from the semiconductor bandgap resonance). The channel waveguide propagation losses also were quite low; the best had an attenuation of less than a 1 dB/cm. High-power laser beams of wavelength near the bandgap of the semiconductor crystallites were propagated in the waveguides and a damage threshold of a few gigawatts per square centimeter was obtained for picosecond pulses.

The first nonlinear optics experiment performed in the waveguides was degenerate four-wave mixing.[1] This was a difficult experiment since three independent coupling prisms all had to be optimized. Peak reflectivities up to 1% were obtained with nanosecond pulses. These experiments demonstrated that the nonlinearities survived the ion-exchange process.

To verify that bandfilling in the crystallites is the dominant nonlinearity in the channel waveguides, we measured with picosecond pulses the change in transmission with wavelength of channel semiconductor-doped Schott glass waveguides at various power levels.[2] A clear blue-shift of the transmission curves with increasing power indicated that the nonlinearity is due to band filling in the semiconductor doped crystallites, establishing the electronic nature of the nonlinearity. Pump-probe experiments showed that up to 90% of the absorption could be bleached out in a few cases, and that the recovery time of the nonlinearity was $\cong$20 picoseconds.

All of the preceding characterization experiments led to the demonstration of switching for the first time in a semiconductor-based nonlinear directional coupler with picosecond recovery times.[3-5] When the pulse power was increased to near the saturation threshold for the nonlinearity, the ratio of the power emerging from the two channels changed by approximately 30%, which corresponds to all-optical switching. The "turn-on" was essentially instantaneous, and the coupler nonlinearity relaxed in ≅20 picoseconds. This meant that switching can be implemented for pulse trains with pulse-to-pulse separations of ≅50 picoseconds for cross-talk less than 20dB. The physical origin of the switching was differential bleaching of the absorption between the two channels, as expected from the figure of merit for this material. It was not a refractive but rather an absorptive effect.

We have induced a change in the transmission of a nonlinear Mach-Zehnder interferometer of ≅20% with increasing input power. Since the same nonlinearity is involved in both arms of the interferometer, the differential phase shift required for switching was achieved by using an unequal path for the two channels. The switching mechanism also was bleaching of the absorption.[3]

3. Nonlinear Grating Devices in InSb Waveguides

We have investigated all-optical switching functions using gratings in an InSb waveguide geometry. This device is potentially very important since it requires the smallest figure of merit of all of the all-optical switching devices studied theoretically by us to date. The most important grating device is a distributed feedback grating whose reflection and transmission properties can be tuned optically (Fig 1b). Switching is obtained in both the transmitted and reflected signals. InSb was used because it has very large nonlinearities in the infrared.

The InSb films were MBE grown onto GaAs substrates at Bell Labs Holmdel. Using fabrication techniques developed in our laboratory, we were able to fabricate multiple gratings with different periodicities on a single waveguide. The most sophisticated device consisted of two long period gratings for coupling radiation into and out of the waveguide, as well as a short period distributed feedback grating located between the two couplers. The operative nonlinearity unfortunately was thermal and, therefore, was slow compared to an electronic nonlinearity. We tried very hard to use the near-band-gap electronic nonlinearity, but failed despite the high quality of the films, which were single crystal. (Indicators of quality were the X-ray diffraction patterns and the losses that were identical to bulk material losses.) We speculate that the carrier recombination time is decreased for the thin film versus the bulk form of InSb, hence reducing the nonlinearity beyond the power capability of our laser to utilize. But, our numerical simulations have shown that the response using the distributed feedback gratings is essentially the same for electronic and thermal nonlinearities.[6]

The primary goal was to investigate nonlinear switching via distributed feedback gratings. We have fabricated distributed feedback gratings with transmission coefficients on the order of 1% or less on Bragg resonance, i.e., very efficient gratings. By changing the power of the guided wave beam incident onto the grating, we have all-optically tuned the grating characteristics by approximately one grating bandwidth.[6] This was found by measuring the wavelength dependence of the grating transmission coefficient at both high and low powers. Therefore, when the power was varied at a fixed wavelength near the Bragg resonance, a power-dependent reflection and transmission of the beam was observed of the type suitable for all-optical switching. In the best case, a change in grating reflection by a factor of 20 was observed.[7]

We have demonstrated that one guided wave beam (a control beam detuned far from Bragg resonance) can be used to tune the grating reflectivity experienced by a second guided wave beam near the Bragg resonance. This is simple to implement in a

waveguide that supports two modes, each with a different propagation wavevector. In this scenario, the first beam changes the refractive index in the grating region and tunes the grating away from the Bragg resonance for the second beam. This is a form of light-by-light modulation.

The diffusive (in space) nature of the thermal nonlinearity also allowed us to demonstrate different forms of bistability during the in-coupling process.[8-11] The feedback mechanism necessary for bistability is provided by heat diffusion. Essentially four different experiments were performed. Bistability in the input grating coupler was observed in both the reflected and transmitted signals.[10,11] The power needed to switch was reduced by using the input coupler under study also as an output coupler for a high-power guided wave beam of a different waveguide mode.[8] That is, the outgoing beam biases the grating coupler for the incoming beam. The backward traveling bias beam was coupled into the waveguide by the second grating coupler. The total power required for bistability is actually reduced because of the non-reciprocal nature of a grating coupler.

A second method to further decrease the power required for bistable switching was devised. A distributed feedback grating was used to reflect the in-coupled guided wave back onto the input coupler, thus, effectively providing a bias beam.[8] The switching power is reduced further because the distributed feedback grating itself is nonlinear and, thus, its reflectivity increases with increasing in-coupled power.

Finally a rarely seen type of bistability was found under a very special operating condition. The periodicity of the grating out-coupler was accidentally chosen so that the radiation coupled into the substrated was at 90^0 to the film and substrate surfaces.[8] The resonances set up across the sample interfered with the normal out-coupled (into air) signal to produce "butterfly" bistability. We unfortunately are not aware of any applications of this effect outside of its aesthetics.

These nonlinear grating experiments verified our initial projections that distributed feedback gratings can be used for switching.

4. Conclusions

This work has shown that all-optical switching operations can be performed with nonlinear directional couplers and with nonlinear gratings. There subsequently has been a great deal of work done on nonlinear directional couplers by other groups. Switching in such devices, while imperfect, is common. The nonlinear grating work is still unique and should be pursued further to multiple switching gratings and to nonlinear beam scanners for interconnect problems.

5. Publications

1. A. Gabel, K.W. DeLong, C.T. Seaton and G.I. Stegeman, "Efficient degenerate four-wave mixing in an ion-exchanged semiconductor-doped glass waveguide," Appl. Phys. Lett. 51(21):1682-1684 (1987).

2. C.N. Ironside, T.J. Cullen, B.S. Bhumbra, J. Bell, W.C. Banyai, N. Finlayson, C.T. Seaton and G.I. Stegeman, "Nonlinear optical effects in ion-exchanged semiconductor doped-glass waveguides," JOSA B 5(2):492-495 (1988).

3. N. Finlayson, W.C. Banyai, E.M. Wright, C.T. Seaton, G.I. Stegeman, T.J. Cullen and C.N. Ironside, "Picosecond switching induced by saturable absorption in a nonlinear directional coupler," Appl. Phys. Lett. 53(13):1144-1146 (1988).

4. N. Finlayson, G. Assanto, W.C. Banyai, K.W. DeLong, A.H. Gabel, G.I. Stegeman, C.N. Ironside, T.J. Cullen and J. Bell, "Nonlinear optics in semiconductor-doped glass waveguides," Proceedings of II International Symposium on Surface Waves in Solids and Layered Structures (in press).

5. G. Assanto, N. Finlayson, W.C. Banyai, G.I. Stegeman, C.N. Ironside and T.J. Cullen, "Recent Progress in Semiconductor-Doped Glass Waveguides," Proceedings of the 2nd International Conference of the Japanese New Glass Society (in press).

6. G. Assanto and G.I. Stegeman, "Optical bistability in nonlocally nonlinear periodic structures," Appl. Phys. Lett. 56(23):2285-2287 (1990).

7. J. Ehrlich, G. Assanto and G.I. Stegeman, "All-optical tuning of waveguide nonlinear distributed feedback gratings," Appl. Phys. Lett. 56(7):602-604 (1990).

8. G. Assanto, J.E. Ehrlich, and G.I. Stegeman, "Feedback enhanced bistability in grating coupling into InSb waveguides," Opt. Lett. 15(8):411-413 (1990).

9. J. Ehrlich, G. Assanto and G.I. Stegeman, "Butterfly bistability in grating coupled thin film waveguides," Opt. Commun. 75(5,6):441-446 (1990).

10. J.E. Ehrlich, G. Assanto, G.I. Stegeman and T.H. Chiu, "Guided-wave bistability in indium antimonide thin films," J. Quant. Electron (in press).

11. J.E. Ehrlich, G. Assanto and G.I. Stegeman, "Nonlinear guided-wave grating phenomena," Proceedings of SPIE Conference (in press).

Theses

1.   "Nonlinear Grating Structures in InSb Waveguides," J.E. Ehrlich, Optical Sciences Center, University of Arizona, 1989.

2.   "Optical Nonlinearities in Semiconductor Doped Glass Channel Waveguides," W.C. Banyai, Optical Sciences Center, University of Arizona, 1988.